arXiv:hep-ph/9502206v1 1 Feb 1995

January 1995

LPTHE Orsay 95-04

LPT Strasbourg 95-01

SPhT Saclay T95/04

HIGGS PHENOMENOLOGY OF THE SUPERSYMMETRIC MODEL WITH A GAUGE SINGLET

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Abstract

We discuss the Higgs sector of the supersymmetric standard model extended by a gauge singlet for the range of parameters, which is compatible with universal soft supersymmetry breaking terms at the GUT scale. We present results for the masses, couplings and decay properties of the lightest Higgs bosons, in particular with regard to Higgs boson searches at LEP. The prospects differ significantly from the ones within the MSSM.

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1. Introduction

The search for the Higgs boson belongs to the most interesting tasks of future experiments such as LEP 200. The prospects are particularly attractive in supersymmetric models, where the lightest neutral Higgs scalar cannot be too heavy. Most of the analysis of a supersymmetric Higgs sector, e.g. at LEP 1 [1], is performed within the minimal supersymmetric standard model (MSSM). The Higgs sector of the MSSM involves only two unknown parameters, which allows to obtain relations between the masses and couplings of the different particles [2]. (These relations get somewhat modified, however, due to radiative corrections which depend on additional parameters as the softly supersymmetry breaking interactions.)

In this paper we consider a modest extension of the MSSM, which amounts to the addition of a gauge singlet superfield to the Higgs sector [3-5]. Subsequently this model will be called the (M+1)SSM. The (M+1)SSM has some attractive theoretical features: the superpotential can be chosen to be scale invariant, thus there is no "μ-problem" as in the MSSM. Assuming relations among the susy breaking terms at a large scale M_{GUT} (such as, e.g., universal gaugino masses, scalar masses and trilinear scalar couplings) the model has the same number of free parameters as the MSSM in spite of the presence of the additional singlet superfield.

It is evident, that in the (M+1)SSM the parameters in the Higgs sector such as masses and couplings to the Z-boson differ significantly from the MSSM. It is thus desirable to interpret the experimental findings independently from the relations between the parameters within the MSSM. On the other hand it would be helpful to have an idea of the ranges of the masses and couplings, which are theoretically allowed within the (M+1)SSM.

If one allows for arbitrary independent variations of all parameters of the (M+1)SSM at the weak scale, a large range particle masses and couplings can be

obtained [5-8]. There are obvious constraints on the parameters, however, which should be imposed: the effective potential, e.g., has to have the correct properties: the minimum where the $SU(2) \times U(1)$ symmetry is broken as desired has to be the absolute minimum; charged and/or coloured fields as sleptons, squarks and charged Higgs scalars are not allowed to obtain vevs. In addition present experimental lower limits on sparticle masses should be satisfied.

Finally one can invoke theoretical prejudices such as universal gaugino masses, scalar masses and trilinear scalar couplings at M_{GUT}. A complete scan of the parameter space of the (M+1)SSM, which is consistent with all these constraints, has been performed [9]. Recently also certain deviations from universal susy breaking terms at M_{GUT} have been investigated [10], but the corresponding sets of low energy parameters did not exceed the ranges covered by the assumption of universality.

In the present paper we will present results for the range of low energy parameters within the Higgs sector of the (M+1)SSM, which is obtained from the scan over universal susy breaking terms at M_{GUT}. We will focus on the masses of the lightest Higgs scalars and pseudoscalars, their couplings to the Z boson, and comment on their decay properties. In particular we will be interested in the question which region of the parameter space is accessible to LEP 2.

2. The Model

The particle content of the Higgs sector is given by the two MSSM Higgs doublet superfields H_1 and H_2, and the additional gauge singlet superfield S. The top quark sector is important because of its radiative corrections to the parameters of the Higgs sector. It involves the right handed top quark T_R, and the left handed doublet Q containing the left handed top and bottom quarks T_L and B_L. The relevant part of the superpotential is of the form

$$W = h_t \; Q \; H_2 \; T_R^c + \lambda \; H_1 \; H_2 \; S + \frac{\kappa}{3} S^3 \tag{1}$$

and involves three dimensionless Yukawa couplings h_t, λ and κ, but no mass term. The only dimensionful parameters of the model are the supersymmetry breaking gaugino masses, scalar masses and trilinear couplings:

$$\left(\mu_1\lambda_1\lambda_1 + \mu_2\lambda_2\lambda_2 + \mu_3\lambda_3\lambda_3 + h_t\ A_t\ Q\ H_2\ T_R^c + \lambda A_\lambda\ H_1\ H_2\ S + \frac{\kappa}{3}S^3\right) + h.c.$$

$$+m_1^2|H_1|^2 + m_2^2|H_2|^2 + m_S^2|S|^2 + m_Q^2|Q|^2 + m_T^2|T|^2 \qquad (2)$$

where λ_1, λ_2 and λ_3 are the gauginos of the $U(1)_Y$, $SU(2)$ and $SU(3)$ gauge groups, respectively.

The scalar potential contains the standard F and D terms, the supersymmetry breaking terms and in addition one loop radiative corrections of the form

$$V_{rad} = \frac{1}{64\pi^2} S\ tr\left[M^4 \ell n\left(M^2/Q^2\right)\right] \qquad (3)$$

where we only take the top quark and squark loops into account. We include, however, the numerically important contributions beyond the leading log approximation, which depend on A_t, the vev of S and the difference between M_Q^2 and M_T^2 [11]. Q^2 denotes the renormalization point of $\mathcal{O}(M_{Susy}^2)$.

After minimization of the potential and the removal of the Goldstone modes the physical particle content in the Higgs sector is given by three neutral scalars, two neutral pseudoscalars and one charged Higgs boson. The corresponding mass matrices in terms of the parameters of the low energy effective potential can be found in [5-9]. In addition there are two (Dirac-) charginos, and five two-component neutral fermionic states ("neutralinos").

As mentioned above, in this paper we constrain the range of the low energy parameters of the model by requiring universal supersymmetry breaking terms at $M_{GUT} \sim 10^{16}$ GeV. Thus we start by scanning over $\sim 10^6$ points in the five dimensional parameter space of the model at M_{GUT}, given by the three Yukawa couplings λ_0, κ_0 and h_{t0} and the ratios of the supersymmetry breaking terms

m_0/μ_0, A_0/μ_0. In each case we integrate the renormalization group equations down to the electroweak scale of $\mathcal{O}(100)$ GeV, determining thereby the parameters of the low energy theory appearing in eqs. (1) and (2).

Next we minimize the low energy effective potential numerically in each case, including the radiative corrections eq. (3). We check, whether we have found the absolute minimum of the potential, and verify, whether squarks or sleptons do not assume vevs, which would break color and/or electromagnetism [4, 12].

In the remaining cases we determine the overall scale of the dimensionful parameters by identifying $< H_1 >^2 + < H_2 >^2$ with $2M_Z^2/(g_1^2 + g_2^2)$, and compute the physical masses of all particles. Then we impose the following experimental constraints: concerning the top quark, we require the pole mass m_{top} to be just roughly two standard deviations within the CDF value [13], i.e. 150 GeV $< m_{top} <$ 200 GeV. We demand the charginos and sneutrinos to be heavier than 45 GeV, and the neutralinos to be either heavier than 45 GeV or to couple sufficiently weakly to the Z boson such that they do not contribute more than 7 MeV to its invisible width. The lightest neutralino is always the lightest sparticle within the range of parameters obtained finally, and the other sparticles turn out to be automatically sufficiently heavy such that they satisfy the present experimental limits. (In particular the charged Higgs boson is heavier than 135 GeV, hence it will play no role at LEP 2.)

3. Higgs Masses and Couplings

The first question concerns the upper limit on the mass of the lightest Higgs boson h. Due to the radiative corrections to the scalar potential, eq. (3), this upper limit depends on the scale of the supersymmetry breaking terms, notably on the stop masses m_Q^2, m_T^2 and the trilinear coupling A_t. Within the present procedure, however, no automatic upper limit on the scale of supersymmetry breaking is obtained. On the other hand the present procedure makes it evident, that more

and more fine tuning is required for large scales of supersymmetry breaking, i.e. the density of points in the parameter space decreases in the multi-TeV region.

This is visible from fig. 1, where we plot the mass of the lightest neutral Higgs scalar h versus the mass of the gluino as a representative of the scale of supersymmetry breaking, for $\sim$ 5 000 points in parameter space. One finds an upper limit on the mass of the lightest Higgs boson of $\sim$ 140 GeV for a gluino mass below $\sim$ 1 TeV, and an upper limit of $\sim$ 160 GeV for a gluino mass up to $\sim$ 2,5 TeV. (The upper limit on the Higgs mass would decrease by $\sim$ 10 GeV, if the top quark mass would be required to be lighter than or equal to 175 GeV). From fig. 1 one finds that for a large part of the parameter space h will be too heavy to be produced at LEP 2.

On the other hand fig. 1 shows that for some part of the parameter space the lightest Higgs scalar can indeed be very light. (Note that we have not yet included experimental constraints from the unsuccessful Higgs search at LEP 1 at this stage). At this point the question arises, how easily a light Higgs boson can be seen in Z boson decays in this model. A priori two possible processes exist:

$$\begin{aligned} a)\ & Z \to Z + h \\ b)\ & Z \to A + h \end{aligned} \tag{4}$$

where A denotes a neutral pseudoscalar boson; in the following A will be the lightest one among the two pseudoscalars, which exist in the (M+1)SSM. (The other one turns out to be heavier than 120 GeV and will accordingly play no role at LEP2.) Let us first have a look at process a). Generally the lightest Higgs boson h is a superposition of three neutral scalar fields:

$$h = c_1\ h_1 + c_2\ h_2 + c_3\ s \quad . \tag{5}$$

Only the $SU(2)$ doublets h_1 and h_2 (with hypercharges $\pm$ 1/2) couple to the Z boson, the singlet s has no gauge boson couplings. It has been noted before

[5, 6], that the lightest Higgs boson could be dominantly a gauge singlet in the (M+1)SSM. In fig. 2 we show a plot of the coefficient c_3 versus the mass of h for the present sample of points in parameter space. We observe, that indeed the parameter space can be approximately divided into two distinct regions: a region, where h is dominantly gauge singlet (c_3 is close to 1) and possibly very light, and a region, where h is dominantly a gauge non-singlet (c_3 close to 0), but heavier than ~ 55 GeV.

This feature is also visible in a direct investigation of the Z-Z-h coupling, which is relevant for the process a) of (4). If we denote by g_h the strength of this coupling relative to the corresponding coupling in the non-supersymmetric standard model, we find that g_h is given by

$$g_h = \frac{c_1 < h_1 > + c_2 < h_2 >}{\sqrt{< h_1 >^2 + < h_2 >^2}} \quad . \tag{6}$$

In fig. 3 we plot the logarithm fo g_h^2 versus M_h for the present points in parameter space. Again we see that for g_h to be close to 1, M_h has to be larger than ~ 55 GeV, whereas there exists a long "tail" towards lighter Higgs masses, but with very small coupling g_h. As a dotted line we show in fig. 3 the boundary of the region in this plane, which has been excluded by LEP 1 [1] (assuming visible Higgs decays, see below). We see that LEP 1 has actually excluded just a tiny part of the parameter space. We also show the boundary of the region which is visible at LEP 2. Here we define visibility by requiring more than 50 events (before any cuts have been applied) for a c.m. energy of 175 GeV and an integrated luminosity of 500 pb^{-1} (dashed line), or for a c.m. energy of 205 GeV and an integrated luminosity of 300 pb^{-1} (full line). Of course the prospects for LEP 2 are better than for LEP 1, but it is also evident that at least via the search for a Higgs scalar even LEP 2 is far from covering the complete parameter space.

Let us briefly comment on the decay properties of the lightest Higgs scalar at this stage. First one has to check, whether invisible decays into neutralino pairs

play a role. Whereas neutralinos could, in principle, still be very light within this model [14], we have found for our range of parameters that within the accessible region for LEP 2, as in fig. 3, the lightest neutralinos are still heavier than $M_h/2$, hence this Higgs decay channel is not open. The lightest Higgs scalar thus decays practically exclusively through its h_1 component of eq. (5), which couples to b quarks and τ leptons with a relative strength as the standard model Higgs boson. The fact that the coefficient c_1 can be tiny (for c_3 close to 1) decreases, of course, the width of the lightest Higgs scalar considerably; its lifetime does not yet become long enough, however, for allowing it to travel macroscopic distances such that a displaced vertex could be visible. Hence the same search criteria as for the standard model Higgs boson can be applied to the lightest Higgs scalar for the present region of parameter space of the (M+1)SSM.

Now we turn to the Higgs production process b) of (4). First we investigate, in fig. 4, which range of masses of the lightest pseudoscalar boson A as a function of M_h is allowed. We see that, within the plotted range, M_A satisfies approximately $M_A \sim 2 \cdot M_h$. The allowed region in the M_A-M_h plane is different from the one within the MSSM [2, 15]. This is not surprising, however: here the lightest Higgs scalar h is dominantly gauge singlet, thus in this region of the parameter space the Higgs sector of the (M+1)SSM differs substantially from the MSSM.

It turns out, moreover, that for $M_A \leq 130$ GeV also the lightest pseudoscalar A is to more than 99 % a gauge singlet state. Unfortunately both facts imply that within the range of the M_A-M_h plane, which is kinematically accessible to LEP 2, the Z-A-h coupling is vanishingly small. The process b) of (4) can thus not be used to test a part of the present parameter space.

Of course, prospects for the discovery of a light Higgs scalar h, which is dominantly gauge singlet, look generally quite dim. Fortunately it turns out, however, that under such circumstances the second lightest Higgs scalar H cannot be too

heavy [5-7]. This offers some hope to access the Higgs sector of the (M+1)SSM via this particle. Thus, in fig. 5, we plot the logarithm of g_h^2 versus the mass M_H of the second lightest Higgs scalar. Indeed we see that, for small g_h, M_H cannot be too large. The range of M_H corresponding to an "invisible" lightest Higgs scalar h, 90 GeV $\leq M_H \leq$ 150 GeV, can, however, hardly be reached by LEP 2. Below 150 to 160 GeV, on the other hand, a visible Higgs scalar h or H is guaranteed to exist within this model, provided the gluino mass (as a measure of the susy breaking scale) does not exceeed 2 to 3 TeV.

Let us return to LEP 2, where the only access to the Higgs sector turned out to be the process a) of (4), which can cover the part of the parameter space indicated in fig. 3. It is of interest to compare this part of the parameter space with the one, which is accessible via direct sparticle searches. In fig. 6 we plot the mass of the lightest chargino versus the mass of the lightest charged sleptons (sleptons of different generations are nearly degenerate) for the range of parameters obtained within our scanning procedure. We see that, if LEP 2 can detect charginos or charged sleptons with masses up to $\sim$ 90 GeV, an essential part of the parameter space can be tested. We have to face the question, whether this part of the parameter space covers completely the one accessible via the search for a Higgs scalar.

In fig. 7 we show the points in the parameter space, which are visible via the Higgs production process a) of (4), versus the masses of the lightest chargino and charged sleptons. Whereas for most of these points the lightest charginos or the charged sleptons are indeed lighter than 90 GeV, we find nevertheless a non-vanishing region in parameter space, in which the lightest Higgs scalar can be observed at LEP 2, but both the lightest chargino and the charged sleptons are too heavy.

4. Conclusions

We can summarize our results as follows. The extension of the MSSM by a gauge singlet requires a fresh look at the phenomenology within the Higgs sector. The lightest neutral Higgs scalar can be somewhat heavier than in the MSSM. In particular the couplings of the lightest scalar and pseudoscalar to the Z boson can be substantially reduced. For the range of parameters consistent with universal soft susy breaking terms at M_{GUT} we have found that a pseudoscalar Higgs is either too heavy or couples too weakly for LEP 2, and the search for a Higgs scalar can cover only a part of the parameter space. If the lightest Higgs scalar is dominantly gauge singlet and hence practically invisible, the Higgs boson search has to put up with second lightest scalar; fortunately, however, this state will then at least be accessable by the next generation of e^+ e^- linear colliders [7].

For the model presented in this paper the search for charginos or sleptons at LEP 2 seems to be somewhat more promising than the Higgs boson search; nevertheless a range of parameters exist, for which a Higgs boson, but no sparticle would be visible.

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Figure Captions

Fig. 1: Mass of the lightest Higgs scalar (in GeV) versus the gaugino mass (in TeV). Unless stated otherwise, the plots are produced using a representative sample of $\sim$ 5 000 points in the parameter range as described in the text.

Fig. 2: Singlet component c_3 of the lightest neutral Higgs scalar versus its mass (in GeV).

Fig. 3: Logarithm of the ZZh coupling squared versus m_h. Dotted line: region excluded by LEP 1. Dashed line: region visible at LEP 2 at a c.m. energy of 175 GeV and an integrated luminosity of 500 pb^{-1}. Full line : region visible at LEP 2 at a c.m. energy of 205 GeV and an integrated luminosity of 300 pb^{-1}.

Fig. 4: Mass of the lightest pseudoscalar A versus m_h.

Fig. 5: Logarithm of the ZZh coupling squared versus the mass of the second neutral Higgs scalar.

Fig. 6: Mass of the lightest chargino versus the mass of the lightest charged slepton.

Fig. 7: As in fig. 6 for only those points in parameter space, which are visible in $Z^* \to Zh$ at LEP 2.

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Fig. 1

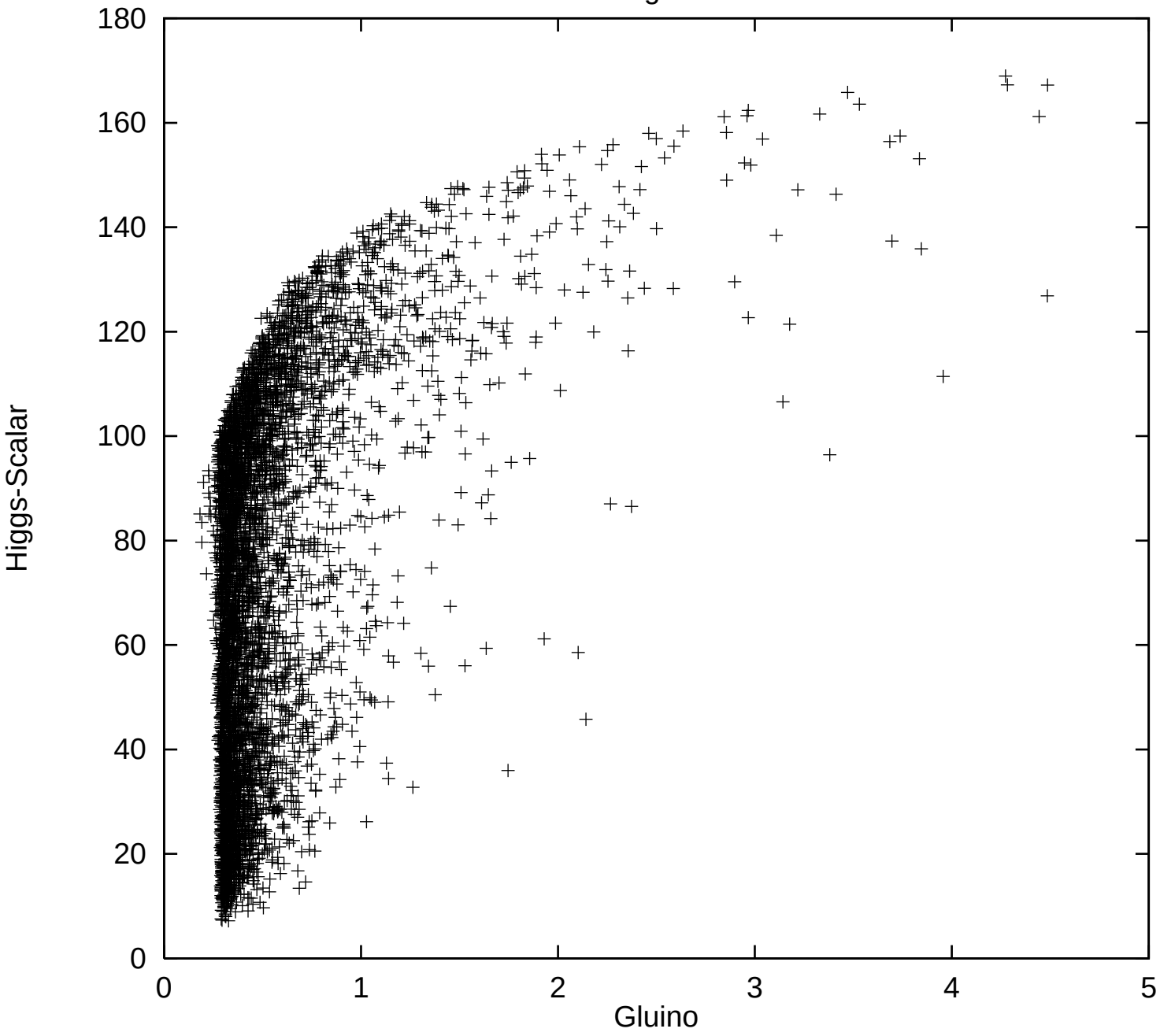

Fig. 2

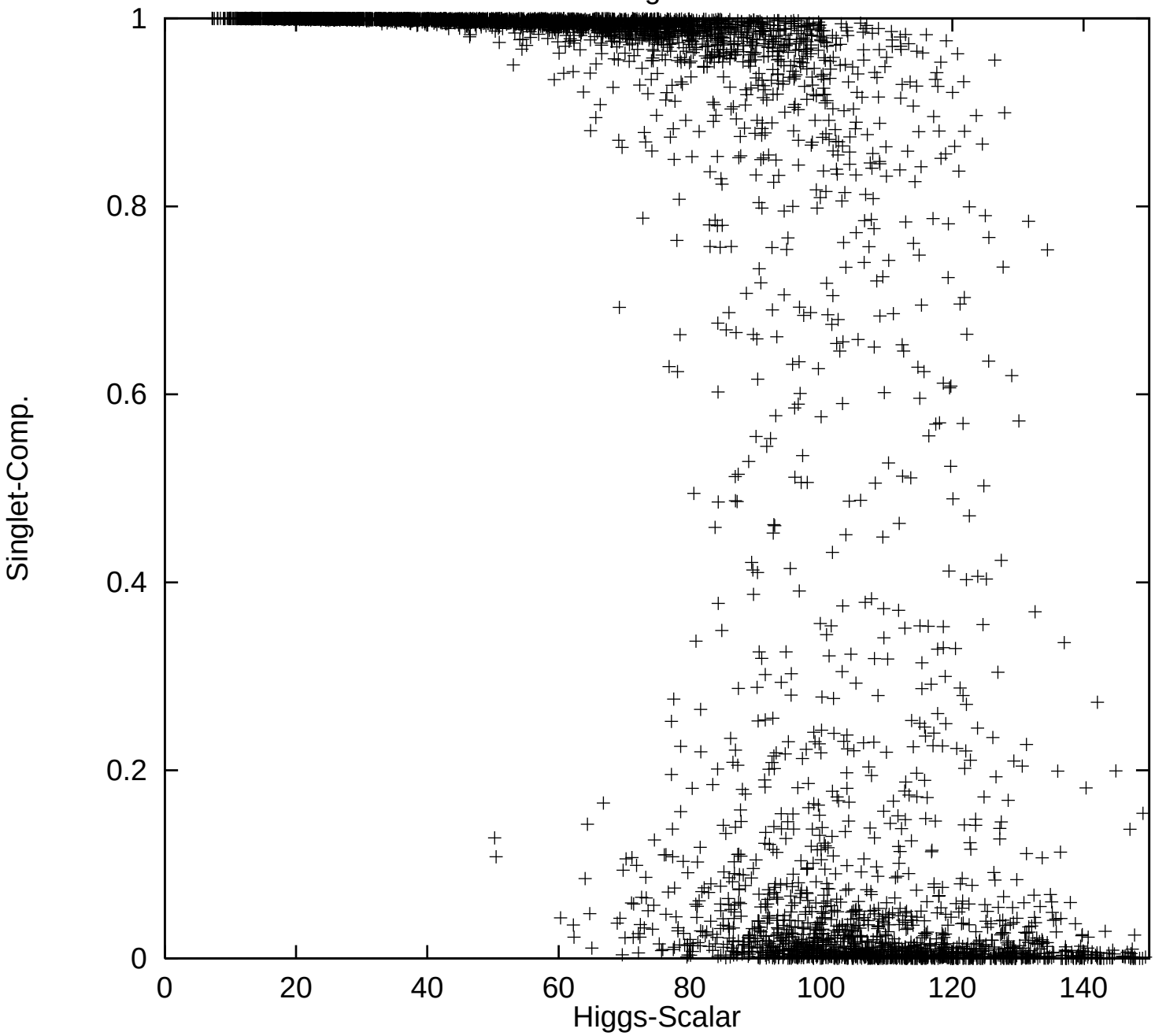
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Fig. 3

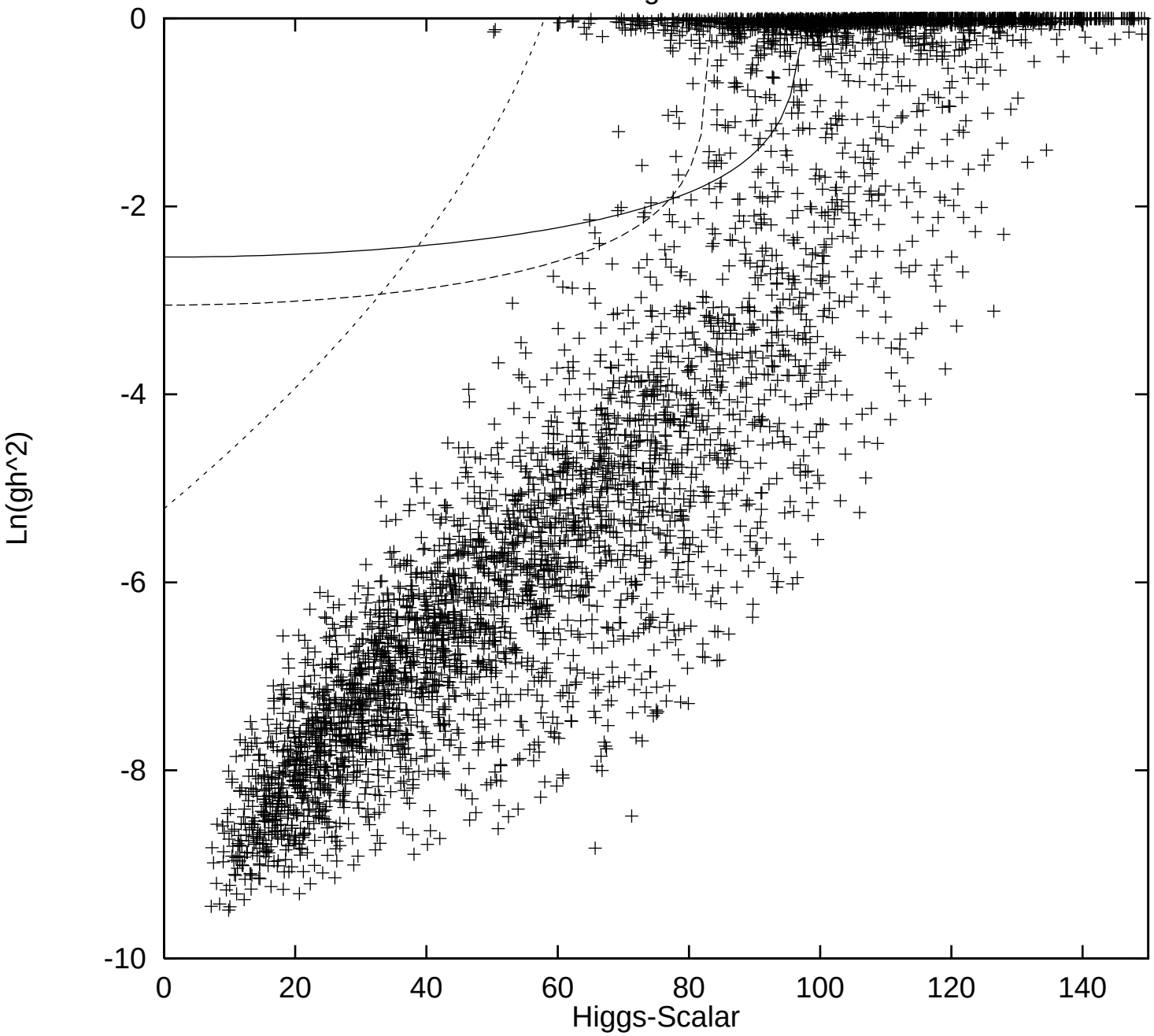

Fig. 4

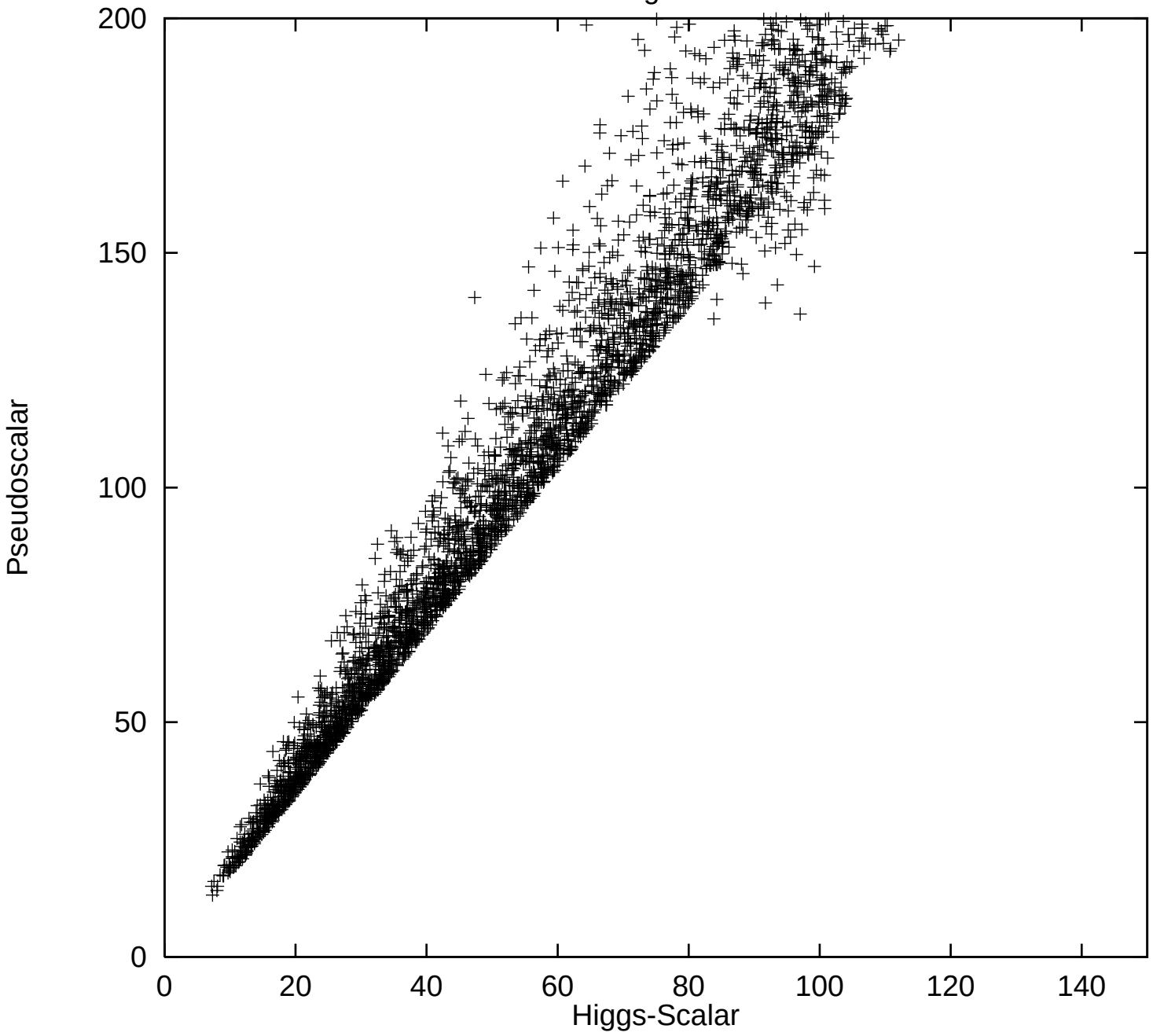
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Fig. 5

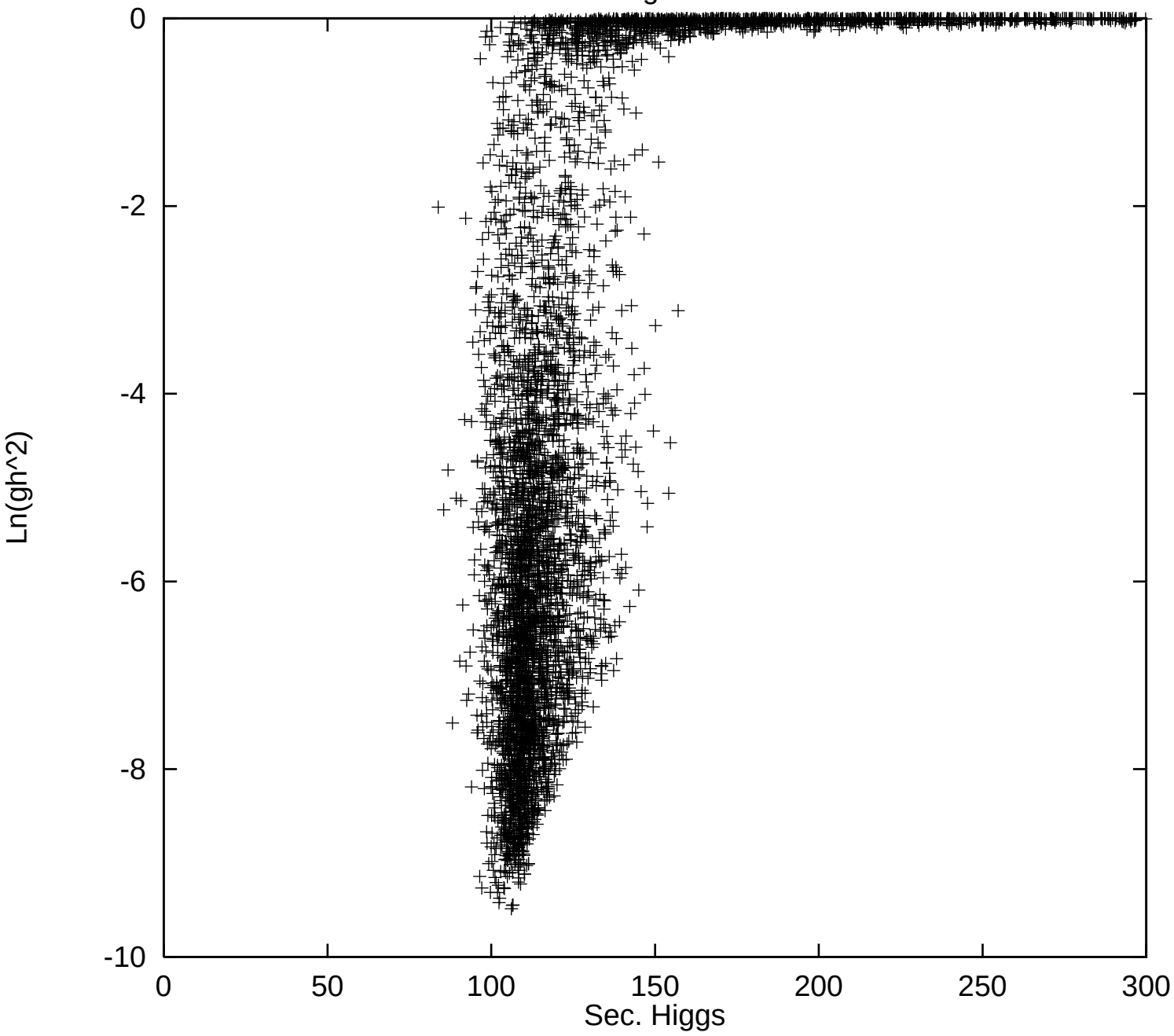


Fig. 6

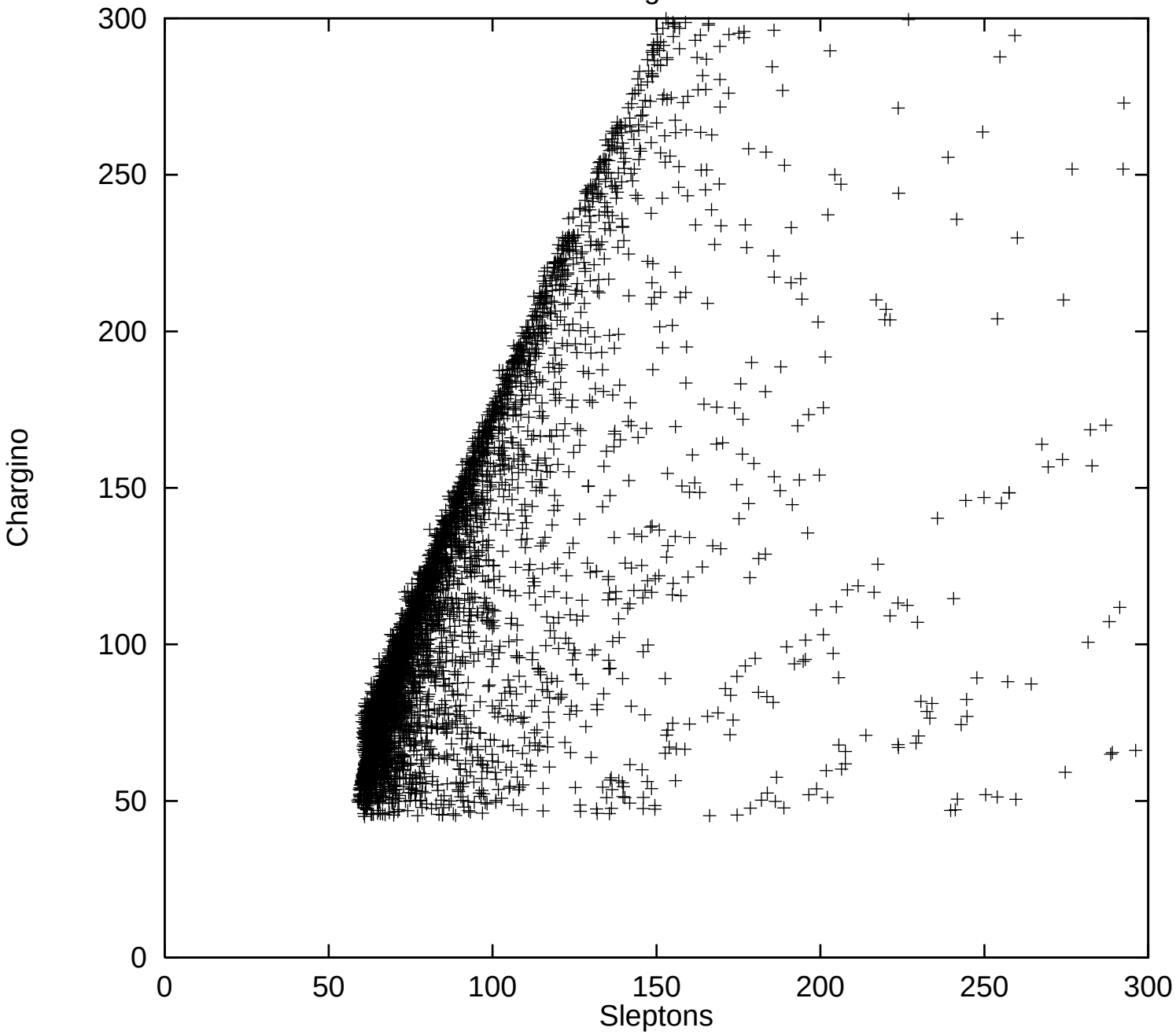
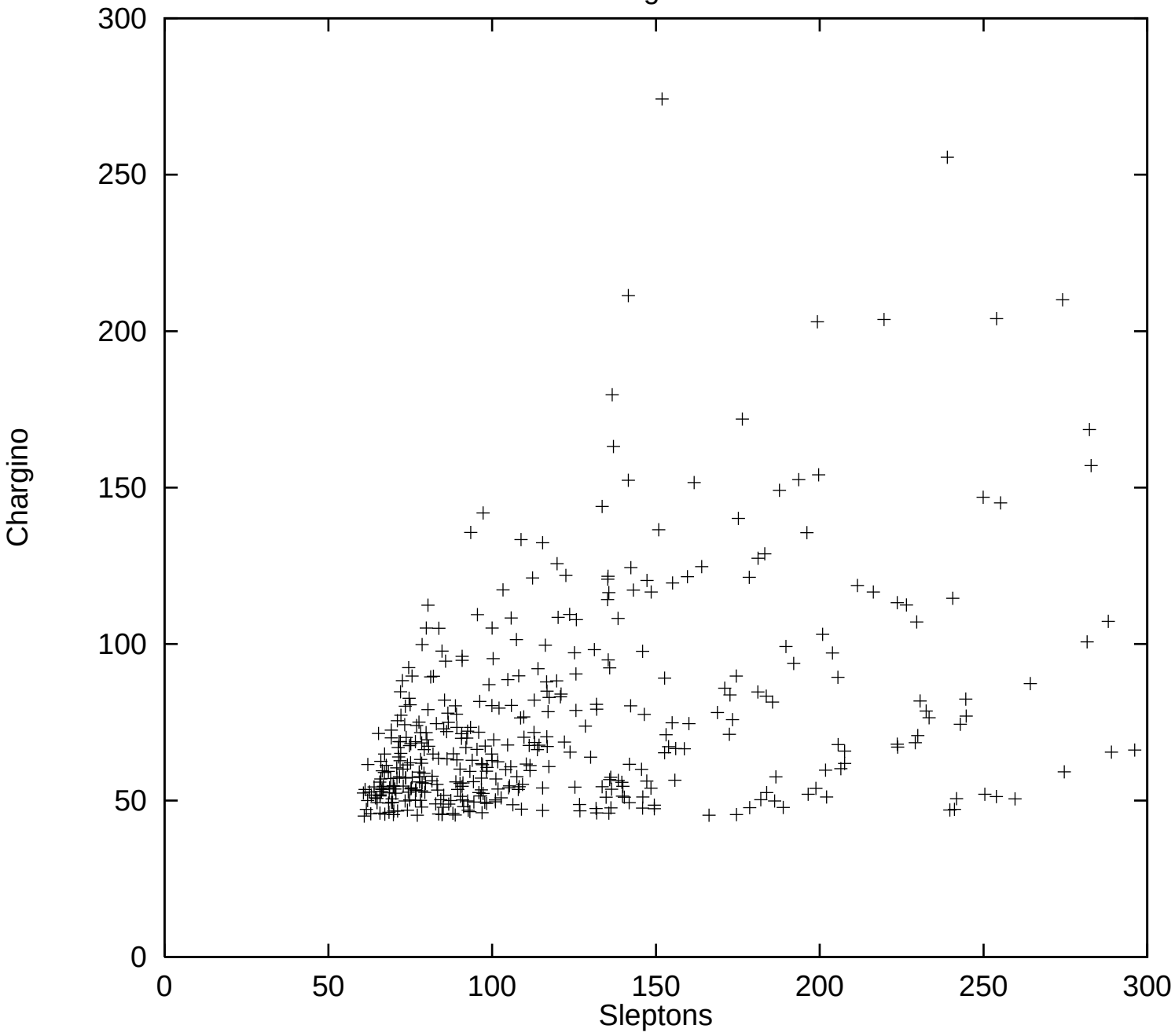


Fig. 7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